Proto-clusters and the clustering of distant galaxies and radio sources

Huub Röttgering,[a] Emanuele Daddi,[b] Roderik Overzier,[a] Richard Wilman[c]

[a]*Sterrewacht Leiden, PO Box 9513, 2300 RA Leiden, The Netherlands*

[b]*European Southern Observatory, Garching, Münich, Germany*

[c]*Department of physics, Durham, United Kingdom*

Abstract

The clustering properties of objects in 3 different radio surveys (NVSS, FIRST and BOOTES-WSRT) and 2 near-infrared surveys (the "Daddi field" and the FIRES survey) are investigated and compared with studies of various samples of galaxies, AGN and clusters. At $z \sim 1$, it seems that the 2dF optical quasars have a correlation length a factor of about 2 less than powerful radio galaxies at similar redshifts. This indicates that these two classes of object can not be "unified" by postulating that their main difference is due to their evolution being at a different stage. It seems much more likely that these QSOs are predominantly located in field galaxies, while the powerful radio sources are located preferentially in early types. Furthermore, it appears that both the extremely red objects (EROs) from the IR surveys and the more luminous radio sources are similarly clustered and as such are the most clustered objects known in the $z > 1$ Universe. Even at $z \sim 3$ the red J-K galaxies from the FIRES survey are similarly strongly clustered, at a level of about 3 times higher than Lyman break galaxies. These clustering properties are consistent with EROs and radio galaxies being similar objects at different stages of their evolution. Locally, the most clustered population of objects are clusters of galaxies. Since the progenitors of these objects – proto-clusters – will therefore also be highly clustered, a good way to locate proto-clusters is to target fields with very powerful and potentially highly clustered distant $z > 2$ radio sources. The techniques that are currently being used for locating and studying these proto-clusters are briefly discussed.

Key words: Galaxies: high-redshift; Galaxies: active; Galaxies: clusters

1 Introduction

In the local Universe, the distribution of galaxies is observed to be complex; massive clusters and super-clusters exist as well as large empty regions, the so called voids. The clusters seem to be connected by a web of filaments and walls of galaxies. For a nice visual illustration of the beauty of the local galaxy distribution, see for example the maps based on the two-degree Field (2dF) Galaxy Redshift survey by Peacock et al. (2001). The spatial fluctuations in the galaxy distribution can be connected with measurements of the cosmic microwave background (CMB) anisotropies. Lahav et al. (2002) showed that within a model based on a flat ΛCDM Universe, both measurement sets can be fit simultaneously. Ingredients of such a model include the growth of clustering of dark matter halos, evolution of the bias parameter (i.e. how do galaxies trace mass at different epochs) and the history of merging of galaxies. The present challenge for observers is to measure the clustering properties not only for large samples of local galaxies, but also for rarer objects such as active galaxies. Furthermore, measurements of the clustering of galaxies, clusters and AGN as a function of redshift, luminosity and mass will in detail constrain models of the evolution of structure in the Universe.

In this contribution, we first discuss a number of radio and near-infrared surveys and the analysis of the clustering of the various classes of objects in these surveys. It appeared that radio galaxies at $z \gtrsim 1$ are among the most clustered objects known in the $z \gtrsim 1$ Universe. They are clustered at a level similar to extremely red galaxies. Since in the local Universe clusters of galaxies are the most clustered objects (Bahcall and Soneira 1983), the highly clustered distant radio galaxies seemed good targets to hunt for forming clusters – proto-clusters. Finally, we briefly discuss the use of powerful radio galaxies as probes of such distant clusters. For more extensive discussions, we refer to other contributors to these proceedings, including those of Best, Buttery, Brand, Croft, Kurk, Wold, and Venemans.

2 Clustering

A measure of the clustering of an ensemble of objects is the correlation function $\xi(r)$, where r is the distance. The correlation function measures the excess chance over a random distribution of detecting an object a distance $r + \delta r$ from a given object. The total chance δP of detecting an object within a volume δV is therefore given as:

$$\delta P = n[1 + \xi(r)]\delta V,$$

where n is the volume density of the objects. In most cases, the spatial correlation function can be parametrised as a power law:

$$\xi(r) = (r/r_0)^{-\gamma},$$

where r_0 is the scale length at which the expected overdensity of objects is twice that over Poissonian.

Often, for a survey only the positions of objects on the sky are known and not the true spatial distances. The angular spatial correlation $w(\theta)$ is then used to measure the angular clustering:

$$\delta P = n[1 + w(\theta)]\delta\Omega,$$

where $\delta\Omega$ is an infinitesimal area on the sky at a distance θ from the given object. The corresponding power law is then defined as:

$$w(\theta) = A\theta^{1-\gamma}.$$

If for a sample the redshift distribution and amplitude and slope of the angular two-point correlation function are known, the spatial correlation function can be derived, using the Limber equation. For a detailed account of the usage of the two-point correlation function we refer to the book by Peebles (1980).

2.1 Samples

During the last few years we have analyzed the clustering properties in 5 different surveys, the NVSS, FIRST and BOOTES radio surveys and a wide and a very deep near IR survey. We will discuss these in turn.

2.1.1 First and NVSS

The NVSS (Condon et al. 1998) and the FIRST (Becker et al. 1995) radio surveys have both been carried out by the VLA at 1.4 GHz. They cover large areas of down to a 5 sigma level of 2.5 and 1 mJy respectively. Overzier et al. (2003) analysed in detail the clustering properties of these samples. A similar analysis has been performed by Blake and Wall (2002). The main result is that the two-point correlation function can be described as consisting of two power laws (see Fig. 1).

The power law that dominates on the smaller scales is due to extragalactic radio sources that are often comprised of two distinct lobes. The median separations of these lobes are 10 - 20 arcsec at flux levels of a few Jy at 151 MHz,

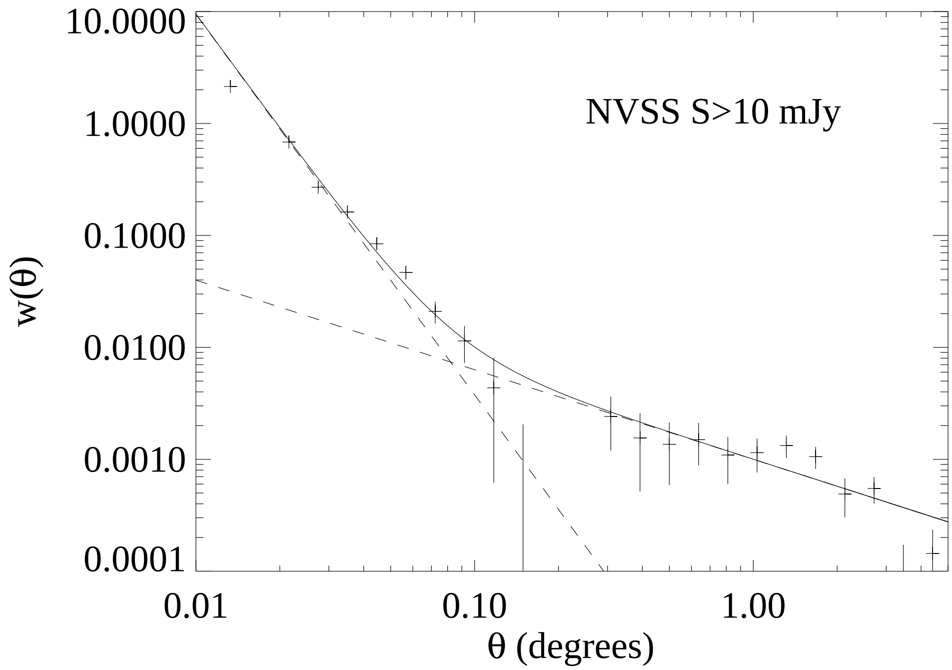

Fig. 1. The angular two-point correlation function of $S > 10$ mJy NVSS sources (from Overzier et al. 2003).

with a long tail to many arcminutes (Eales et al. 1985). To model this power-law, the local angular size distribution as found by Neeser et al. (1995) was taken and evolved to higher redshift according the median of the distribution getting smaller at higher redshifts as $(1+z)^{-1.7}$. Using the radio luminosity function by Dunlop and Peacock (1990), we can then model the contribution to the physical doubles to the angular two point correlation function. This simple model provides a good fit to the power law on small scales. The power law at larger scales is due to the cosmological clustering of radio sources. Interestingly, the number of radio sources in these surveys is so large that we can investigate whether the amplitude of the cosmological angular correlation function varies with flux density. Indeed it does, and in the range 3 to 50 mJy has a fairly constant amplitude of $\sim 10^{-3}$, rising to values of 5 to 10 times higher between 50 and 300 mJy. To convert these amplitudes into correlation lengths we use redshift distributions as calculated from the radio luminosity models of Dunlop and Peacock. At the higher flux density levels these are accurate enough for our purpose. At the lower flux levels, these models and the resulting redshift distribution are less accurate, mainly due to a lack of samples at these flux levels with complete redshift information. One of the aims of the CENSORS project (Best et al., in prep) is to provide such a sample. Using these redshift distributions, we find that the correlation length varies from 5 Mpc for the samples with flux densities less than 50 mJy to around 15 Mpc at 200 mJy. We note that if the redshift distribution for the fainter sample turns out to be broader than inferred from the Dunlop and Peacock model the resulting correlation length will be larger.

2.2 Bootes survey

The Westerbork Bootes Deep survey covers approximately 7 square degrees and is centered at $14^{\rm h}32^{\rm m}05.75^{\rm s}$, $34°16'47.5''$ (J2000). It consists of 42 discrete pointings, with enough overlap to ensure a uniform sensitivity across the entire field, with a limiting sensitivity of 28μJy ($1\sigma_{\rm rms}$). The catalog contains 3172 distinct sources, of which 316 are resolved by the 13×27 arcsec beam. At these faint flux densities a significant fraction of the sources originates in starbursting galaxies rather than AGN. One of the aims of this survey is therefore to study the clustering properties of starbursts. NOAO is carrying out a deep combined optical and infrared study of this field which will provide photometric redshifts for virtually all the radio sources. Since these data are not yet available, Wilman et al. (2003) started the analysis of the clustering of the radio sources with the study of the angular correlation function. Applying the models of Overzier et al. (2003) to estimate what fraction of measured amplitude of the correlation function was found to be due to faint double FRII radio sources, led to the conclusion that all the signal could be explained by these sources. Upper limits on the cosmological clustering amplitude are, however, consistent with the clustering of the radio-loud AGN being diluted by the more weakly clustered IRAS-type starburst galaxies.

2.3 Daddi-field

With the initial aims of obtaining a well defined sample of extremely red objects, Daddi et al. (2000) surveyed a 700 arcmin^2 region down to a limiting magnitude of approximately $K = 19.$ and found about 400 objects with very red colours of $R-K > 5$. The subsequent analysis of the clustering of these red objects found a large amplitude of the correlation function of $> 10^{-2}$. Furthermore, it appeared that the amplitudes were a strong function of $R-K$ colour in the range $1 < R-K < 7$, with the reddest objects being most strongly clustered. These measurements were subsequently confirmed by other groups using independent surveys (Roche et al. 2002, Firth et al. 2002). This high signal is most easily explained if the vast majority of these EROs are ellipticals in the redshift range $1 < z < 1.5$. Such a narrow redshift range stems from a combination of two effects. First, at these magnitude levels objects only are so red if the Balmer break is redshifted beyond $z \sim 1$. Second, the bright magnitude level of K=19, ensures that objects with $z > 1.5$ are exceedingly rare in such samples. Using such a narrow redshift distribution, the resulting correlation length is 8-10 Mpc. While r_0 is large compared to local field galaxies, it is consistent with predictions of semi-analytic galaxy formation models, where the decrease in clustering with redshift of dark matter halos is compensated by an increase in their bias (e.g. Kauffmann et al. 1999). This

is further evidence that the majority of these EROs are ellipticals rather than SCUBA type starburst galaxies. Such starburst galaxies exhibit a large range in redshift, much larger than expected for ellipticals in this sample. The resulting correlation length inferred from the measured amplitude would then be unrealistically large. This adds further weight that the majority of EROs in this sample are $z \sim 1.5$ ellipticals.

2.4 FIRES survey

The Faint InfraRed Extragalactic Survey (FIRES) is a very deep infrared survey centered on the Hubble Deep Field South using the ISAAC instrument mounted on the VLT (Franx et al. 2000). With integration times of more than 33 hours for each of the infrared bands J, H and K, limiting magnitudes of, 26.0, 24.9, and 24.5 respectivily are reached (Labbé et al. 2003). A major advantage of observing this field is that multicolour HST photometry is available resulting in accurate photometric redshifts. A detailed analysis of the clustering of galaxies in this survey was presented by Daddi et al. (2003). One of the interesting results was the finding of a relatively large clustering amplitude for a K-selected sample down to $K = 24$, at a level comparable with measurements at $K \sim 19$. To explain this high level of clustering, the existence of a highly clustered population of galaxies is required with a comoving correlation length of $r \sim 10$ Mpc. To investigate the clustering of distant galaxies further, we defined a sample of 105 objects with photometric redshift estimates $2 < z < 4$. The 48 galaxies with $J - K > 1.7$ have a correlation length of 8.2 ± 1.1 Mpc, a factor of about 2 larger than the bluer galaxies in this sample. These red galaxies are a factor 3-4 more clustered than Lyman break galaxies down to a level of $V_{606} = 27$. A detailed analysis of the properties of this highly clustered population, including characteristic mass and number density, suggests that they are the objects that should be identified with the progenitors of local massive early type galaxies.

3 Clustering as a function of redshifts for galaxies and AGN

The comparison of the clustering properties of galaxies and AGN as a function of redshift is a powerful tool to constrain models of their evolution. In addition to the measurements for clustering in the samples just discussed, measurements for clustering of various types of objects have been gathered from the literature (for details see Overzier et al. 2003). For local clusters, early and late type objects we took the measurements as presented in Postman et al. (1992), Carlberg et al. (1997, 2000) and Norberg et al. (2002). For the optical quasars, we used the measurements for the 2dF quasars from Croom et al.

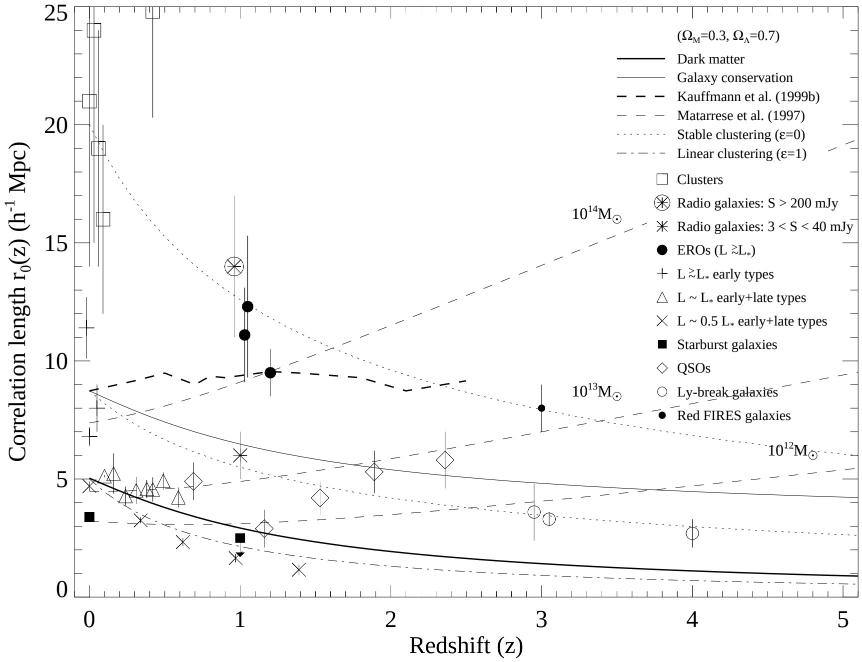

Fig. 2. The redshift evolution of galaxy clustering in a ΛCDM Universe. See Overzier et al. (2003) for details. In addition to the plot presented by Overzier, also plotted here are the correlation lengths r_0 for the FIRES galaxies between $2 < z_{phot} < 4$ from Daddi et al. (2003). A nice representation of this figure showing actual images of the various objects rather than symbols can be found at our website: http://www.strw.leidenuniv.nl/˜overzier/r0.html.

(2001). For the very distant Universe, the clustering analysis for Lyman break galaxies are taken from Adelberger (2000) and Ouchi et al. (2001)

In Figure 2 we show how the correlation length changes as a function of redshift for the various galaxy and AGN samples. In addition, a number of models for the evolution of clustering are plotted.

The first important conclusion that can be drawn is that at redshifts $z \gtrsim 1$ powerful radio sources are among the most clustered population. Interestingly, the distant EROs have similar correlation lengths. This suggest that EROs and powerful radio galaxies might be similar objects at a different evolutionary stage. This is supported by their K-band magnitudes being more or less similar (e.g. Dunlop 2001). Furthermore, the number density of both classes is of the same order, provided that a limited life time of the radio sources of the order of 10^7 years is taken into account (Mohan et al. 2002; Willott et al. 2001).

The inferred correlation lengths for the powerful radio sources is a factor of 2-3 larger than that of the optical quasars. If this is correct, then these optical quasars and radio sources can not be "unified" through an evolutionary scheme. The much more likely explanation is that QSOs in general reside in

a field population. Consistent with many other lines of evidence (e.g. Best et al. 1998), the powerful radio sources are hosted by very massive systems.

In the local universe, clusters have the largest correlation length. Detailed models of the evolution of clustering (Refregier et al. 2002), indicate that r_0 of clusters should remain rather constant with redshift. $z > 1$ clusters and proto-clusters therefore should be clustered at a level equal to or higher than powerful radio galaxies. An obvious test whether there is a direct link between powerful radio sources and clusters is to establish that powerful radio sources are indeed often residing in clusters.

4 Powerful radio galaxies as probes of distant clusters

There a number of additional arguments that distant powerful radio sources reside in (proto-)clusters (e.g. Best et al. 1998). An important one is that these radio galaxies seem to reside in the most massive, luminous and gas rich systems for a given redshift and are therefore likely to be located in rich environments. For example, the Hubble K-band diagram shows that at $z > 1$ radio galaxies are 1-2 magnitudes brighter than the brightest objects found in "field surveys" (e.g. de Breuck et al. 2002). From dust, CO, HI absorption and emission line studies, it is clear that radio galaxies contain a large reservoir of gaseous material that is forming stars at high rates. (e.g. Papadopoulos et al. 2000; Archibald et al. 2000). The high star formation rates and deep spectroscopy with 10-m class telescopes reveal UV spectra that are remarkably similar to nearby star forming galaxies (Dey et al. 1997).

Direct evidence that radio sources reside in dense environments comes from the high rotation measures (> 1000 rad / m^2) observed for a significant fraction of the $z > 2$ radio sources (e.g. Carilli et al. 1997). These are similar to the rotation measures determined for radio sources that reside in the rich local clusters.

The conclusive proof that at least a fraction of the radio sources are in proto-cluster type environments comes from the discovery of significant galaxy over-densities around a number of high redshift radio galaxies. Currently the most efficient technique is to hunt for Lyα emitting galaxies using a combination of narrow-band imaging and multi object spectroscopy. The state of the art in this field is presented in this workshop by Venemans. In each of the 5 well-studied objects with $2 < z < 4.1$ more than 20 Lyα emitters have been found. Other techniques of pinpointing galaxies are being developed. They rely on deep mm/sub millimeter observations (e.g. Ivison et al. 2000), sensitive X-ray imaging (e.g. Pentericci et al. 2002), multi-colour imaging with one filter blue-ward of the Lyman break, or infrared Hα imaging. For one proto-cluster

(1138−262) at $z = 2.2$ a number of these techniques have been used, suggesting that the distribution of Hα emitters, Lyα emitters and extremely red objects are all different (Kurk et al., these proceedings). This indicates that those proto-clusters are comprised of a number of populations that differ in age and/or metallicity.

References

[1] Adelberger, K. 2000, in ASP Conf. Ser. 200: Clustering at High Redshift, 13

[2] Archibald, E. N., Dunlop, J. S., Hughes, D. H., et al. 2001, MNRAS, 323, 417

[3] Bahcall, N. A. & Soneira, R. M. 1983, ApJ, 270, 20

[4] Becker, R., White, R., & Helfland, D. J. 1995, ApJ, 450, 559

[5] Best, P., Longair, M. S., & Röttgering, H. J. A. 1998, MNRAS, 295, 549

[6] Blake, C. & Wall, J. 2002, MNRAS, 329, L37

[7] Carilli, C. L., Röttgering, H. J. A., van Ojik, R., Miley, G. K., & van Breugel, W. 1997, ApJS, 109, 1

[8] Carlberg, R. G., Cowie, L. L., Songaila, A., & Hu, E. M. 1997, ApJ, 484, 538

[9] Carlberg, R. G., Yee, H. K. C., Morris, S. L., et al. 2000, ApJ, 542, 57

[10] Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693

[11] Croom, S. M., Shanks, T., Boyle, B. J., et al. 2001, MNRAS, 325, 483

[12] Daddi, E., Cimatti, A., Pozzetti, L., et al. 2000, A&A, 361, 535

[13] Daddi, E., Röttgering, H. J. A., Labbé, I., et al. 2003, ApJ, 588, 50

[14] De Breuck, C., van Breugel, W., Stanford, S. A., et al. 2002, AJ, 123, 637

[15] Dey, A., Van Breugel, W., Vacca, W. D., & Antonucci, R. 1997, ApJ, 490, 698

[16] Dunlop, J. & Peacock, J. 1990, MNRAS, 247, 19

[17] Dunlop, J. S. 2003, The redshifts of bright sub-mm sources, astro-ph/0101297

[18] Eales, S. A. 1985, MNRAS, 217, 179

[19] Firth, A. E., Somerville, R. S., McMahon, R. G., et al. 2002, MNRAS, 332, 617

[20] Franx, M., Moorwood, A., Rix, H., et al. 2000, The Messenger, 99, 20

[21] Ivison, R. J., Dunlop, J. S., Smail, I., et al. 2000, ApJ, 542, 27

[22] Kauffmann, G., Colberg, J. . M., Diaferio, A., & White, S. D. M. 1999, MNRAS, 307, 529

[23] Labbé, I., Franx, M., Rudnick, G., et al. 2003, AJ, 125, 1107

[24] Lahav, O., Bridle, S. L., Percival, W. J., et al. 2002, MNRAS, 333, 961+

[25] Mohan, N. R., Cimatti, A., Röttgering, H. J. A., et al. 2002, A&A, 383, 440

[26] Neeser, M. J., Eales, S. A., Law-Green, J. D., Leahy, J. P., & Rawlings, S. 1995, ApJ, 451, 76

[27] Norberg, P., Baugh, C. M., Hawkins, E., et al. 2002, MNRAS, 332, 827

[28] Ouchi, M., Shimasaku, K., Furusawa, H., et al. 2001, American Astronomical Society Meeting, 199, 0

[29] Overzier, R. A., Röttgering, H. J. A., Rengelink, R. B., & Wilman, R. J. 2003, A&A, 405, 53

[30] Papadopoulos, P. P., Röttgering, H. J. A., van der Werf, P. P., et al. 2000, ApJ, 528, 626

[31] Peacock, J. A., Cole, S., & Norberg et al.. 2001, Nature, 410, 169

[32] Peebles, P. J. E. 1980, The large-scale structure of the Universe (Research supported by the National Science Foundation. Princeton, N.J., Princeton University Press, 1980. 435 p.)

[33] Pentericci, L., Kurk, J. D., Carilli, C. L., et al. 2002, A&A, 396, 109

[34] Postman, M., Huchra, J. P., & Geller, M. J. 1992, ApJ, 384, 404

[35] Refregier, A., Valtchanov, I., & Pierre, M. 2002, A&A, 390, 1

[36] Roche, N. D., Almaini, O., Dunlop, J., Ivison, R. J., & Willott, C. J. 2002, MNRAS, 337, 1282

[37] Willott, C. J., Rawlings, S., & Blundell, K. M. 2001, MNRAS, 324, 1

[38] Wilman, R. J., Röttgering, H. J. A., Overzier, R. A., & Jarvis, M. J. 2003, MNRAS, 339, 695